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by Richard J. Weber
Lewis Research Center
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TECHNICAL PAPER proposed for presentation at Distribution Conference sponsored by the American Gas Association
St. Louis, Missouri, May 1-4, 1967

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Liquefied Natural Gas as a Fuel for Supersonic Aircraft

by Richard J. Weber*
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

ABSTRACT

Current jet airplanes utilize kerosene or gasoline-type fuels. Liquid methane, however, is superior in terms of heating value, cooling capacity, and possibly cost. When it is applied to the difficult supersonic transport mission, payload capacity is estimated to increase by 30 percent, with a similar reduction in direct operating cost.

Many problems must be solved before the concept can be considered to be feasible. If it is actually adopted, the airlines would consume up to six trillion cubic feet of natural gas per year.

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*Chief, Mission Analysis Branch

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INTRODUCTION

The purpose of this paper is to review studies performed at the NASA concerning the use of liquefied natural gas in future supersonic commercial aircraft. The data presented herein are primarily abstracted from references 1 and 2, which are written from the viewpoint of the aeronautical engineer. An effort is made in this paper to recognize those factors of particular interest to the gas industry.

The major characteristics of a typical supersonic transport (SST) design† are compared in figure 1 with those of a contemporary subsonic transport. Note that the range-payload performance of the SST is substantially inferior to that of the subsonic craft -- and this, despite the favoring larger size of the SST. The obvious "plus" for the SST is that its speed is about three times greater. This provides an immediate benefit for the passenger in reduced trip time. It also provides a benefit for the airline operator in greater productivity for the airplane; as a consequence of this factor, the SST is expected to be no more costly to operate than the subsonic plane.

Much effort has been devoted in the past few years to bettering the performance of the SST through improvements in the efficiency of the engines and the aerodynamics and structure of the airframe. As a result it is now believed that a useful commercial vehicle can be built. The present U.S. schedule calls for the SST to enter service in 1974. Somewhat smaller and slower airplanes are being developed by England-France and the USSR, which may be available even sooner.

Nevertheless, there is still considerable room for further improvement in airplane performance. In figure 1 we see that the heaviest single component of the airplane is the fuel. Since it is expended during every flight, the fuel is also very important to the operating expense of the airplane. Hence, it is a natural question to ask whether changing the fuel type might not be desirable.

The fuel used in all present jet aircraft is either kerosene or a gasoline-kerosene blend called JP. The properties of this fuel are compared with a number of alternative fuels in table I. Of primary importance to airplane performance is the first column, the heat of combustion. The engine fuel consumption and thus the airplane fuel load vary inversely with this number. Methane is the best of the light hydrocarbons in this respect, being 13-percent better than JP. Methane is also best in terms of heat sink capacity, which will be shown later to be very important for supersonic airplanes. (As seen in the table, liquid hydrogen would be even better, but it must be presently ruled out for commercial flight because of its high cost.)

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†The details of the proposed SST vehicle are continually being modified as the engine and aircraft companies refine their designs. The configuration assumed in this paper is an NASA design that is sufficiently representative of supersonic transports for the purposes of this discussion.

The table also points out some serious disadvantages for methane. Its temperature must be kept below -259°F to prevent boiling away, and it is only about half as dense as JP. These qualities will present obvious difficulties in ground handling and airplane design.

ENGINE AND AIRPLANE PERFORMANCE

Engine Design

As a preliminary to presenting typical engine performance, let us consider the problem of engine cooling. Cycle and mission studies have shown that high gas temperatures entering the turbine are necessary for good thermodynamic efficiency during supersonic flight. In contrast to temperatures of 1400-1500°F in current subsonic engines, the goal for the SST engine is 2200°F. Since the available materials for turbine blades can withstand only about 1700°F, the blades must be cooled in some fashion. The usual scheme is to bleed high-pressure air from the compressor exit and duct it through small cooling passages in the turbine blades. The compressor-bleed air is itself at 1000-12000°F, so that this technique for cooling is a difficult and marginal affair.

The high heat-sink capacity of liquid methane can be applied to alleviate this situation and permit much higher turbine-inlet gas temperatures with no increase in blade metal temperature. Two possible schemes for accomplishing this are (1) chill the compressor-bleed cooling air with an air-to-methane heat exchanger, or (2) eliminate the bleed air entirely and run the methane fuel through the blade cooling passages before entering the combustor. This latter scheme is illustrated in figure 2.

The net result of changing from JP to methane fuel is indicated in figure 3. Cruise performance of a turbojet engine is shown in terms of two parameters: specific impulse (a measure of engine fuel consumption) and thrust per unit airflow (a measure of engine size and hence weight). High values of both parameters are desired. Switching from JP to methane at the same turbine inlet temperature increases the specific impulse by approximately 13 percent, as we would expect from the difference in heating values. Raising the temperature, to 2800°F say, yields a small further increase in specific impulse plus a large increase in thrust (for the non-afterburning mode).

Airplane Deisgn

The value of such engine improvements can be judged only through reference to the performance of the complete engine-airplane combination, operating over a typical flight mission. Accordingly, a family of methane-fueled SST airplanes was designed and "flown" (with the help of a high-speed computer) and compared to similar JP-fueled vehicles. The mission was to fly a distance of 4000 statute miles at a cruise speed of Mach 3, with a takeoff gross weight of 460,000 pounds. Various design constraints such as maximum allowable takeoff distance and sonic boom were observed. Within the limits of these constraints, engine and wing size were optimized for maximum payload.

It should be cautioned that, although beyond the scope of the present paper, the details of the assumptions in the previous paragraph can have a great effect on the final result. For example, refer to the sketches in figure 4, which shows the SCAT 15F configuration considered in this study. The upper part of the figure depicts the location of the fuel tanks when JP is used. The lower part shows how methane would be distributed, with its approximately 70-percent greater volume. Small differences in the airplane design concept could easily have resulted in smaller wings than shown. As a consequence the needed methane tank volume would not be available without enlarging the airplane in some fashion. Depending on the designer's ingenuity, the enlargement would cost extra weight and aerodynamic drag, with a consequent penalty to performance. (As a matter of fact, the airplane design that is presently being planned for actual construction has, in addition to a smaller wing, a variable-geometry mechanism in the wing that further reduces the volume available for fuel storage.)

A further caution is sounded concerning the criterion of merit selected for making comparisons. Instead of applying methane to increase the payload, we could have increased the range or reduced the gross weight. The percentage of improvement is not the same for all three cases.

Based on the assumptions of the present study, we find the results given in figure 5. Changing to methane fuel with the same turbine inlet temperature is estimated to yield an increase in number of passengers of 17 percent. Applying the added cooling capacity to raise the temperature from 2200 to 2800°F increases methane's advantage over JP to 31 percent.

It need hardly be mentioned that this striking improvement is attended by some serious design difficulties that must be overcome before the concept becomes a reality. Some of the problems are in the engine, such as developing the technique of cooling with methane previously mentioned. The major problems, however, appear to be associated with the airframe and its operation. One of them, the containment problem, will be discussed in a conceptual fashion.

Fuel boiloff. - Providing sufficient volume for the fuel is only the beginning of the containment problem. Insulation must be used to minimize heat leaks into the fuel during ground hold and cruise, so that excessive boiloff losses will not be suffered. However, the major boiloff problem is one that cannot be cured with insulation. It occurs as the airplane climbs from sea level up to its cruise altitude of about 70,000 feet. Airplane fuel tanks are normally vented to the atmosphere so that the tank pressure is little higher than ambient. This is satisfactory for JP, but disastrous for methane. The methane at its liquefaction temperature of

$-259^{\circ}F$ and one atmosphere of pressure is a boiling liquid. If its pressure is reduced during climb, large amounts of fuel are flashed off as vapor and lost through the vents. This cannot be tolerated.

Proposed solutions fall into two categories: (1) utilize the vapor in some useful fashion, or (2) prevent the vapor from evolving. Under category (1), the only profitable place to use the vapor is in the engine as fuel. This requires a dual fuel system that incorporates auxiliary compressors to achieve a pressure sufficient for injection into the combustors. Even then, more vapor is generally evolved during the early part of flight than the engines can use, so some fuel must inevitably be lost. This approach is undesirable because it adds weight and complexity. Consider category (2). Here we can conceive of several possibilities.

(a) Condense the vapor as fast as it evolves with an on-board liquefaction system; however, the estimated weight of such a system is of the same magnitude as the total airplane weight and so is impractical.

(b) A more feasible modification to (a) is to use a ground system to subcool the methane before it is loaded on the airplane. Tank pressure could now be reduced in flight down to the saturation pressure corresponding to that temperature with no vapor loss. This technique would solve the boiloff problem but causes a new difficulty. Since the pressure of the subcooled fuel is much less than atmospheric, the fuel tanks when at low altitude will tend to collapse inward unless they are pressurized up to about one atmosphere by some other gas. Apart from the undesirable complexity of the system, finding a suitable pressurant is troublesome. For example, nitrogen is too soluble in subcooled liquid methane, and helium is probably too scarce.

(c) Closing off the tank vents and maintaining atmospheric pressure throughout the flight is the most direct way to prevent boiloff. The problem here is that there would be a large pressure differential during cruise, tending to burst the tanks. Redesigning the airplane structure to support this load could cause large weight penalties.

The airplane performance estimates presented herein were based on the use of subcooled methane and included representative fuel system weight penalties. However, this is an area that requires more study.

COST EVALUATION

Since the SST is a commercial application, operating cost is an even more important criterion than payload. To evaluate this factor it is necessary to know the cost of the fuel.

Methane is derived commercially from natural gas, of which it is normally the major constituent. Direct use of liquefied natural gas in the airplane is not desirable, since the other constituents have inferior heats of combustion. However, high purity methane is unnecessary; for example, the inclusion of 10 percent ethane reduces the heating value by only 1/2 percent. Since the non-methane constituents are readily separated in the liquefaction process and are usually of value in their own right (e.g., propane and butane), the cost of liquid methane should be about the same as LNG.

The LNG cost of interest is that delivered to the airplane. This cost will undoubtedly vary around the world, depending on the relative locations of the gas supply and the airport in question. The transport of LNG by ship over large distances is today a commonplace technique. Truck and rail transportation is also available for inland delivery. Based on present costs (of Algerian LNG delivered to England, for example), it is estimated that liquid methane delivered to the airport might run in the order of 2 cents per pound when this transportation technique is used.

Another, more desirable technique is available in many parts of the world where natural gas can be supplied directly to the airport via pipeline. In this case a liquefaction plant would be constructed at the airport. The facility would be similar to the peak-load-shaving plants that are now in operation in several cities of the U.S.A. A preliminary cost estimate has been prepared by the Institute of Gas Technology of an airport facility capable of fueling 50 SST flights per day (10×10^6 lb/day). Based on a capital investment of 45 million dollars, the resulting unit cost is shown in the following table:

Gas at 40 cents per 1000 cu ft	0.94
Fixed charges at 12 percent/year	0.13
Operating cost	0.14
Total, cents/lb	1.21

This estimate does not include the possible benefits of generating valuable by-products or of combined operation with a local peak-shaving facility. The total of 1.21 cents per pound (or 56 cents/million Btu) may be compared to a typical price of 1.8 cents per pound for JP (97 cents/million Btu).

These prices were used to estimate an economic parameter for the SST called "direct operating cost" (DOC). This parameter, which includes fuel cost, maintenance, and depreciation (ref. 3), has been found to provide a useful measure of economic feasibility for commercial aircraft. As shown in figure 6, methane could reduce the DOC by 25 to 35 percent, depending on fuel cost. The significance of reducing DOC can be appreciated by the following simple example: One SST can make three 4000-mile trips per day carrying 200 passengers. A fleet of 500 SSTs can then provide some 400 billion seat-miles per year. A saving of only 0.1 cent/seat-mile saves the airlines 400 million dollars in one year.

CONCLUDING REMARKS

This paper has reviewed recent studies of the application of LNG to future commercial supersonic airplanes. An effort was made to point out both the positive and negative aspects of the concept.

On the negative side, it must be acknowledged that the use of methane in a supersonic airplane causes additional complications in an already difficult design problem. Supplying a new and unusual fuel to major airports around the world will pose both technical and political problems. Questions concerning the safety of the new fuel in commercial operation must be resolved. The long-term availability and delivered cost of LNG is not yet established.

On the positive side, LNG offers a great potential for improving SST performance, not only in terms of payload and operating cost, but also for longer range and higher speed. For example, the benefits of using methane in hypersonic vehicles are even greater than in the SST.

If the concept is actually put into practice, it offers the gas industry a new customer to consume possibly as much as 6 trillion cubic feet per year, i.e., about 20 percent of present consumption (based on an optimistic estimate of 1200 SSTs in service by 1990.)

As yet the concept of employing LNG in aircraft is merely an intriguing speculation. But the potential rewards to both the aeronautical and the gas industries undoubtedly justify extensive research aimed at substantiating the validity of the idea.

REFERENCES

1. Weber, R. J.; Dugan, J. F., Jr.; and Luidens, R. W.: Methane-Fueled Propulsion Systems. AIAA Paper 66-685, June 1966; See also Astronautics and Aeronautics, vol. 4, no. 10, Oct. 1966, pp. 48-55.

2. Whitlow, J. B., Jr.; Eisenberg, J. D.; and Shovlin, M. D.: Potential of Liquid-Methane Fuel for Mach-3 Commercial Supersonic Transports. NASA TN D-3471, July 1966.

3. Anon.: Standard Method of Estimating Direct Operating Costs of Transport Airplanes. Air Transport Association of Am., Aug. 1960.

Table I - Properties of Fuels

Fuel	Heat of combustion,[a] Btu/lb	Heat-sink limit temperature, $^{\circ}F$	Heat-sink, Btu/lb	Density, lb/ft^3	Boiling point, $^{\circ}F$	Freezing point, $^{\circ}F$
JP	18,700	375-700	165-365	50	300	-65
Propane	19,700	850	700	36.5	-44	-306
Ethane	20,200	950	750	33.0	-128	-298
Methane	21,200	1000	1100	26.5	-259	-296
Hydrogen	51,570	1000	4900	4.3	-423	-435

[a]Lower heating value for liquid at boiling point

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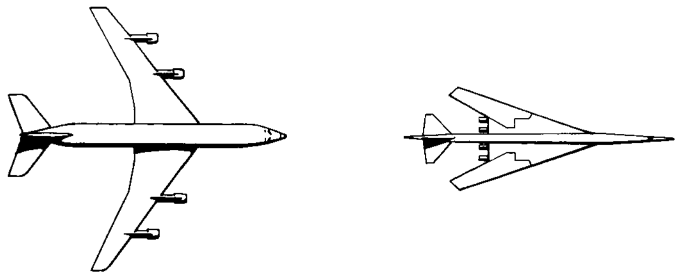

530	Cruise speed, mph	1 900
325 000	Gross weight, lbs	460 000
5 000+	Range, st. miles	4 000
.18	Payload fraction	.09
.38	Fuel fraction	.44

Figure 1. - Typical airplane characteristics.

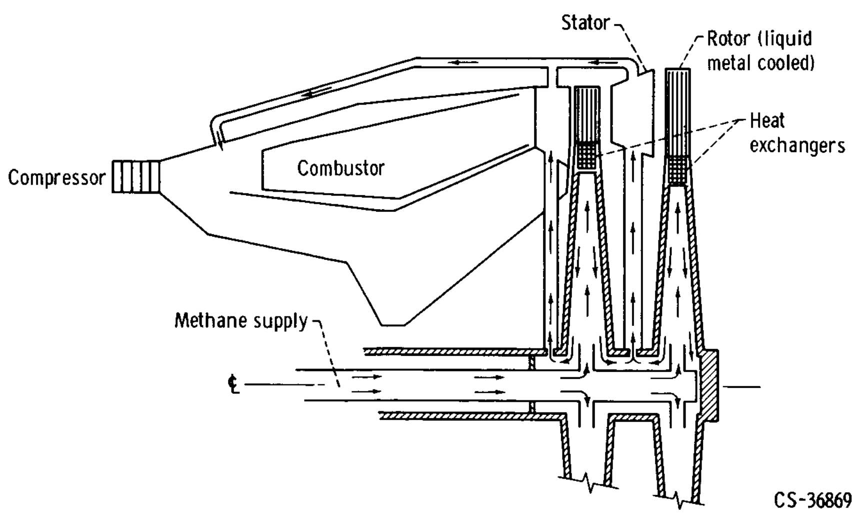

Figure 2. - Elimination of cooling air for turbine cooling.

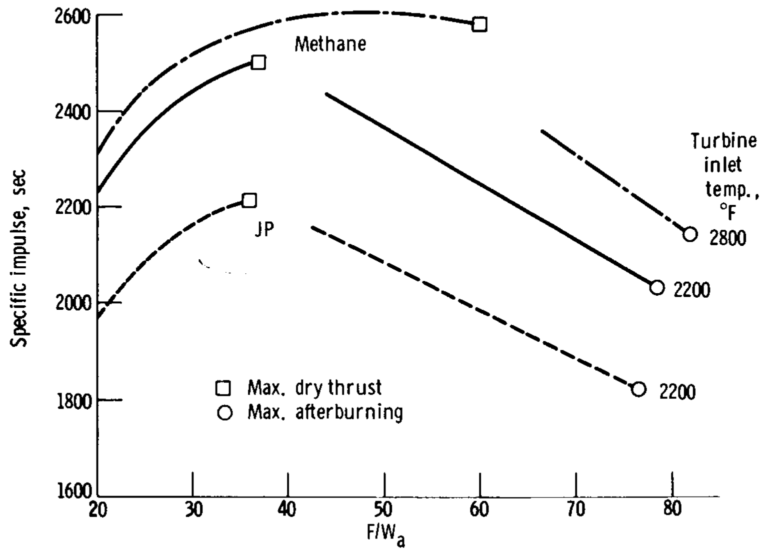

Figure 3. - Turbojet engine performance, Cruise Mach number, 3.0.

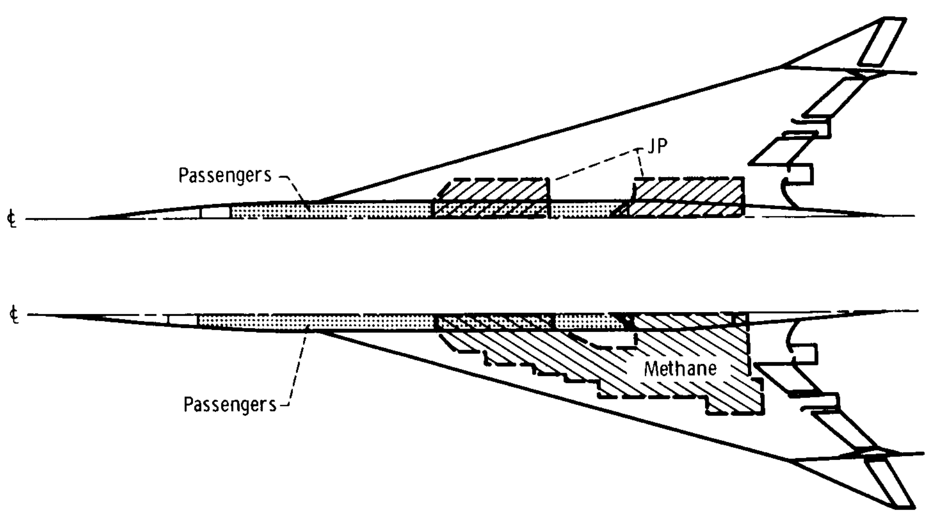

Figure 4. - Fuel storage.

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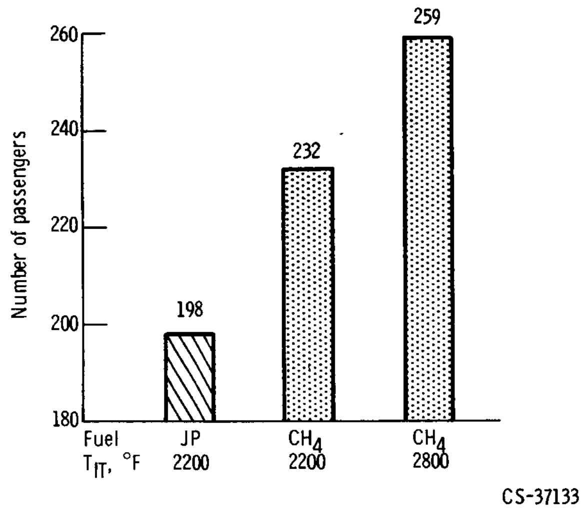

Figure 5. - Methane benefits payload.

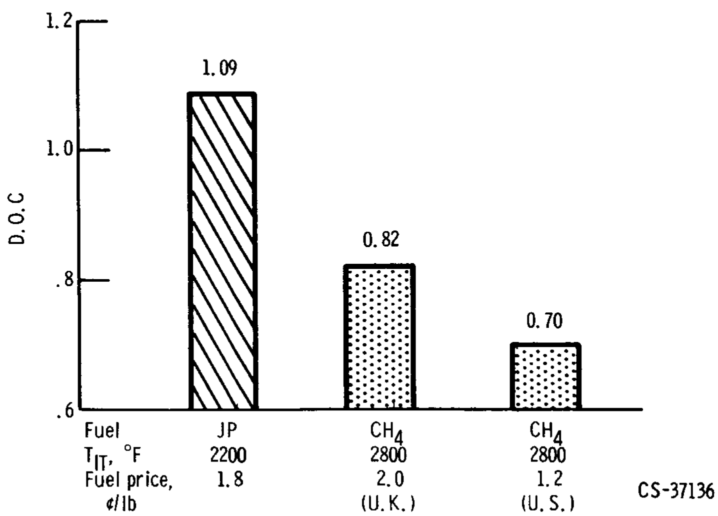

Figure 6. - Methane could lower direct operating cost.